

HST Imaging of Bright Galactic X-ray Binaries in Crowded Fields ¹

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ABSTRACT

We report high spatial resolution *HST* imagery and photometry of three well-studied, intense galactic X-ray binaries, X2129+47, CAL 87 and GX17+2. All three sources exhibit important anomalies, not readily interpreted by conventional models. Each source also lies in a severely crowded field, and in all cases the anomalies would be removed if much of the light observed from the ground in fact came from a nearby, thus-far-unresolved superposed companion. For V1727 Cyg (X2129+470), we find no such companion. We also present an *HST* FOS spectrum and broadband photometry which is consistent with a single, normal star. The supersoft LMC X-ray source CAL 87 was already known from ground-based work to have a companion separated by 0".9 from the optical counterpart; our *HST* images clearly resolve these objects, and yield the discovery of an even closer, somewhat fainter additional companion. Our photometry indicates that contamination is not severe outside eclipse, where the companions only contribute 20% of the light in V, but during eclipse more than half of the V light comes from the companions. The previously-determined spectral type of the CAL 87 secondary may need to be reevaluated due to this significant contamination, with consequences on inferences of the mass of the components. We find no companions to NP Ser (=X1813-14, =GX17+2). However, for this object we point out a small but possibly significant astrometric discrepancy between the position of the optical object and that of the radio source which is the basis for the identification. This discrepancy needs to be clarified.

Subject headings: X-rays: stars — stars: binaries

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1. INTRODUCTION

We discuss the optical identification of three intense, well studied X-ray sources whose optical counterparts remain frustratingly ambiguous, despite literally decades of work. The three sources are members of a very interesting subset of X-ray binary systems: the low mass X-ray binary (LMXRB). In these systems, the large intrinsic L_x/L_{opt} ratio often creates spectacular heating effects on the low-mass normal star, resulting in dramatic photometric and spectroscopic variability as a function of binary phase.

The three sources discussed here have in common the fact that all have suggested optical counterparts that have been well studied spectroscopically and photometrically. However, in all cases these studies have uncovered anomalies that make the identifications suspect, contradictory, or impossible to understand in the current framework. All three objects are also in very crowded fields, two because they are at very low galactic latitude ($b = 1^\circ$ and $b = -3^\circ$), and the third due to membership in the LMC. The combination of the odd optical properties plus the severe crowding has led to multiple suggestions over the years that, in each case, the wrong optical counterpart may have been selected due to the superposition of an additional object of angular separation too small to be resolvable from the ground. The superposition could be foreground/background (the classical “optical double” of unrelated stars), or perhaps even a kinematically-related additional object; for the purpose of this discussion the distinction is unimportant. We have obtained multicolor WFPC2 images of all three objects, to conduct the most sensitive possible probe of the presence of a superposed image, possibly resolving not only the star, but the interpretive contradictions.

The suggestion that superpositions may confuse the analysis of very well-studied galactic X-ray sources is not merely mischievous or a desperate hope: it has already been demonstrated to occur in at least one famous case. The exceptionally intense X-ray source Circinus X-1 (X1516-569) was optically identified almost 20 years ago (Whelan et al. 1977) with an $R = 16$ object, and the identification has been presumed correct since then, based on arcsecond accuracy X-ray and radio positions, as well as very strong $H\alpha$ emission. However, it has recently been demonstrated (Moneti 1992, Duncan et al. 1993) that the “identification” is in fact the wrong star, by more than $1''$! The field proves to have 3 objects within $1''.5$. Had the grouping been slightly more compact than this, only *HST* imaging would be capable of revealing the true nature of the problem. Strangely enough, although Cir X-1 is far from fully understood, no interpretive inconsistencies pointed towards a misidentification (although Argue & Sullivan 1982 and Argue et al. 1984 indeed questioned the identification on astrometric grounds). The three objects studied here, each of which will now be discussed in turn, all do have such existing observational problems, and thus in some sense are even better candidates for superposition than the one object where it is already definitely known to be a problem.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Planetary Camera Imagery

On July 12 and 13, 1995, we obtained (post-refurbishment mission) *HST* Planetary Camera (PC) images of V1727 Cyg, CAL 87, and NP Ser. For each target, exposures through the F336W (2×300 s), F439W (2×200 s), F555W (3×40 s) and F675W (3×50 s) filters were taken; these filters are similar to Johnson U, B, V, and R respectively. The PC frames have been processed through the standard data reduction pipeline at STScI. Further reduction was performed with software written in IDL by E.W.D. or available in the IDL *Astronomy User's Library* (Landsman 1993).

First, each of the sets of two or three exposures were combined with a cosmic-ray rejection algorithm. Although each of these fields is crowded in ground-based images, the PC resolution is such that all sources are well-separated, so we use aperture photometry to measure magnitudes. Aperture corrections are taken from Table 2(a) in Holtzman et al. (1995a). The photometric measurements have not been corrected for geometric distortions in the PC, but the simple correction for charge transfer efficiency losses detailed in Holtzman et al. (1995a) has been applied. Instrumental magnitudes are converted to Johnson UBVR magnitudes using the transformations presented in equation (8) and Table 7 in Holtzman et al. (1995b), where transformation errors are reported to be less than 2%, except in the F336W filter and for sources with unusual colors. The final Johnson magnitudes are the result of a best fit to the 12 transformation equations. Magnitudes and colors for all objects are presented in Table 1. Statistical and read noise uncertainties are 1% or less except for the faint CAL 87 Companions A and B; for these two objects, measurement errors are reported in the table as well. Additional systematic errors for all magnitudes due to uncertainties in detector performance, absolute calibration and filter transformations are $\sim 5\%$.

2.2. Faint Object Spectrograph Data

On October 1, 1993 we obtained (pre-servicing mission) *HST* FOS UV spectra of V1727 Cyg, consisting of two 600 s exposures through the G160L grating and two 600 s exposures through the G270H grating, as part of the FOS Guaranteed Time Observations program. The $4''.3 \times 4''.3$ single aperture was used for all exposures. The raw data were reprocessed with the latest CALFOS reduction algorithm (Lindler & Bohlin 1994) and calibration files; each pair of exposures was combined.

UV spectra of red objects with the FOS are contaminated with some scattered light from longer wavelengths by the diffraction gratings (e.g., Kinney 1993; Koratkar 1995). A simple scattered light subtraction algorithm (Kinney & Bohlin 1993) is applied to the G160L spectra as part of the CALFOS reduction; the correction is calculated from a region on the detector that is

not illuminated by dispersed light. For the G270H spectra, no CALFOS correction is available, as light is dispersed over the entire detector.

After the scattered light correction of 0.0020 and $0.0034 \text{ s}^{-1} \text{ pixel}^{-1}$ to the two G160L spectra, the average count rate in the combined spectrum slowly increases from 0.0015 to $0.0025 \text{ s}^{-1} \text{ pixel}^{-1}$ between 1400 and 2200 \AA . It is likely that these residual counts come from a slight gradient in the scattered light rather than dispersed light from the target. We set upper limits of $3 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ at 1400 \AA and $1 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ at 2200 \AA .

Since there is no CALFOS scattered light correction available for the G270H grating, which covers the $2250\text{--}3300 \text{ \AA}$ region, the correction must be determined empirically. Matching flux levels in the overlap region between the G160L and the G270H gratings is not possible because of the non-detection in G160L. Shortward of 2400 \AA , the count rate is nearly constant. After correcting for the instrumental response we find that the flux level at the shortest wavelengths is well above the upper limit from the shorter wavelength grating. This indicates that the flux below 2400 \AA is due to scattered light, so we correct the spectrum by subtracting the count rate $0.004 \text{ s}^{-1} \text{ pixel}^{-1}$ seen below 2400 \AA .

3. DISCUSSION OF INDIVIDUAL OBJECTS

3.1. V1727 Cyg

The intense LMXRB X2129+470 is of special interest because it shares many properties in common with Her X-1/HZ Her, a very rare but important system. The optical counterpart, V1727 Cyg, at times exhibits large amplitude ($B \sim 1.5 \text{ mag}$) variations with a period of 5.2 hr (Thorstensen et al. 1979), the orbital period of the system. The detailed features of the light curve are similar to those of the HZ Her/Her X-1 system; consequently, the variations are thought to be caused by heating due to X-ray irradiation of the companion’s atmosphere (McClintock et al. 1981). Alternatively, it has been suggested that disk aspect variations are responsible (Chevalier 1989). Early spectra show weak HeII $\lambda 4686$ and CIII/NIII $\lambda\lambda 4640/50$ emission (Thorstensen et al. 1979), which is typical for a LMXRB. Radial velocity studies (Thorstensen & Charles 1982; Horne et al. 1986) imply masses of $0.4 \pm 0.2 M_{\odot}$ for the companion and $0.6 \pm 0.2 M_{\odot}$ for the compact star, an unusually low mass for a neutron star. The X-ray luminosity of the system is also fairly low for a LMXRB, but an X-ray burst found in archival X-ray data (Garcia & Grindlay 1987) confirms that the system contains a neutron star.

The system was thought to be fairly well understood until Pietsch et al. (1986) reported that V1727 Cyg had entered a low state in 1983: the X-ray flux and the large photometric variations vanished. ROSAT observations in the quiescent state (Garcia & Callanan 1995) show that X-ray eclipses continue even in the low flux state. The extended interval of X-ray quiescence prompted a flurry of observations to determine the ellipsoidal variations of the secondary without

the disturbing effect of X-ray heating in order to verify the anomalous low neutron star mass. Surprisingly, *neither photometric variations nor radial velocity variations could be detected* (Thorstensen et al. 1988; Kaluzny 1988; Chevalier et al. 1989; Garcia et al. 1989; Cowley & Schmidtke 1990). The star that is visible in the low state optical spectrum appears to be a normal F8 IV star (Cowley & Schmidtke 1990), although Kaluzny (1988) finds that the colors of the object in the low state are incompatible with colors of an ordinary star. It has been variously proposed that this is due to superposition of a foreground/background star or that X2129+47 is a triple system (Garcia et al. 1989).

If the system is a triple or superposed by a foreground star, then it is possible that all previous optical data taken in the high state are severely contaminated. Contamination by a companion might also explain the anomalous mass inferred for the secondary. Chevalier et al. (1989) present a ground-based image taken in good seeing, motivated by a search for a superposed interloper, and find nothing remarkable.

In our PC observations, the angular resolution is better by an order of magnitude than feasible from the ground, yet V1727 Cyg remains an unresolved single source; there are no significant deviations from the typical WFPC2 PSF with a FWHM of $0''.065$. By subtracting a “Tiny TIM” model PSF (Krist 1993), we set upper limits on possible polluting sources as follows: for $r > 0''.4$, $R > 23.5$; $0''.15 > r > 0''.4$, $R > 22.5$; $0''.04 > r > 0''.15$, $\Delta R > 27 \times r$ where ΔR is the magnitude difference between V1727 Cyg and a possible polluting source. There are no additional sources detected near V1727 Cyg down to $R=23.5$ which have not already been observed by Chevalier et al. (1989) (although pairs B,C and E,F shown in that paper are easily resolved). Our photometry for V1727 Cyg, presented in Table 1, was measured between photometric phase 0.58 and 0.70, according to the ephemeris of McClintock et al. (1982) (derived when this system was still optically eclipsing.) Our UBVR colors are consistent with an F8 type star with $E(B-V) \sim 0.3-0.4$ (best fit $E(B-V)=0.34$). We find no evidence of U excess mentioned by Kaluzny (1988).

Our *HST* spectrum, although obtained during the X-ray low state and thus weakly exposed, provides constraints on the possibility of light from more than just an F8 IV star. After the initial processing described in §2.2, we increase the signal-to-noise by rebinning the spectrum to $\sim 6 \text{ \AA}$, approximately the resolution of the IUE. We then obtained archival IUE spectra of two stars which have similar spectral types to V1727 Cyg, as reported by Cowley & Schmidtke (1990) from their optical spectrum: LWR 15500 of HD 82328 (F6 IV, $V=3.17$) and LWR 15402 of HD 90839 (F8 V, $V=4.83$).

In order to examine a possible difference between the *HST* spectrum of V1727 Cyg and normal stars of similar spectral type, the IUE spectra are reddened with the extinction curve of Savage & Mathis (1979), and then the flux level is scaled by the difference between the V magnitude of V1727 Cyg and the reddened V magnitude of the IUE object. We find that a reddening of $E(B-V)=0.40$ yields an excellent match. A previous estimate of the reddening by Cowley & Schmidtke (1990) from BV photometry yielded $E(B-V) \sim 0.3$. The *HST* spectrum and

the reddened, scaled LWR 15500 spectrum are plotted together in Fig. 1; the other IUE spectrum matches LWR 15500 very closely and is omitted from the plot. Therefore, if the reddening of V1727 Cyg is $E(B-V) \sim 0.3-0.4$, the UV spectral flux and the UBVR colors are consistent with a single F8 star. The M V star discussed by Garcia et al. (1989) as a hypothetical third member of a triple system is many orders of magnitude too faint to alter the spectrum of the F8 IV star, and the system is far too small to be spatially resolvable in our data.

3.2. CAL 87

CAL 87 (Long et al. 1981) is one of only a small number of known LMXRBs in the LMC, and also one of the supersoft X-ray sources, a recently discovered class of X-ray object. It has been pointed out that these extremely X-ray luminous ($\sim 10^{38}$ erg s $^{-1}$) objects may populate our Galaxy in numbers comparable to the more familiar, Eddington-limited 1-10 keV X-ray binaries, but are rarely detected due to severe interstellar photoelectric opacity (van den Heuvel et al. 1992, Yungelson et al. 1996). Although many workers view the compact object in these systems as quite likely an accreting white dwarf (e.g. van den Heuvel et al. 1992; Motch et al. 1994; van Teeseling et al. 1996), Cowley et al. (1990) have presented evidence that CAL 87 contains a black hole, and Hughes (1994) suggests a neutron star companion for the SMC soft-source RX J0059.2–7138, so the situation is unclear.

The optical counterpart of CAL 87, discovered by Pakull et al. (1987), exhibits large photometric variations ($\Delta V \sim 1.2$ mag) with an orbital period of 10.6 hr (Callanan et al. 1989, Cowley et al. 1990). CAL 87 appears to be an eclipsing system with a deep primary minimum and a shallow secondary minimum. Models of the shape of the lightcurve agree well with the eclipse of an extended disk structure, and indicate that the disk is the dominant light source in the system.

The optical spectrum of CAL 87 shows He II $\lambda 4686$ and $H\alpha$ in emission; however CIII/NIII $\lambda\lambda 4640/50$, which is usually seen in LMXRBs, is absent (Pakull et al. 1988). At minimum light, CaII H & K and the G band are seen in absorption; these have been presumed to arise in the secondary and to indicate a spectral type of late F (Cowley et al. 1990). Cowley et al. (1990) measured the radial velocity curve for the He II $\lambda 4686$ line, which presumably arises in the accretion disk. These velocities, plus the inferred spectral type of the secondary, lead to the suggestion that the X-ray source is a black hole.

CAL 87 lies in a very crowded region: Cowley et al. (1991) note a close optical companion only $0''.9$ away. Any photometry of CAL 87 is therefore contaminated unless taken in subarcsecond seeing. Cowley et al. (1991) attempted to detect radial velocity variations of the secondary in the infrared Ca triplet, but find none. They conclude that the spectrum is most likely dominated by the nearby field star and that much better spatial resolution will be necessary to separate the two stars. Small aperture *HST* UV-spectroscopy of the object by Hutchings et al. (1995) presumably does better isolate the X-ray source, but of course yields no information on the nature

of contamination of ground-based photometry and spectroscopy by nearby objects.

Our PC observations easily resolve this companion (which we designate A) and reveal another, fainter and closer, optical companion (B). Figure 2 shows the three objects and the surrounding $7'' \times 7''$ region in the F675W filter, with a limiting magnitude $R \sim 23.5$. Magnitudes for these sources are listed in Table 1. The position angles and distances from CAL 87 for Companions A and B are 335° , $0''.88$ and 210° , $0''.65$ respectively. CAL 87 itself appears to be a single object, with no significant deviations from the typical WFPC2 PSF with a FWHM of $0''.077$.

Using the photometry of all sources in the PC frame, 4 color-magnitude diagrams are presented in Fig. 3; objects mentioned in this discussion are labeled on the diagrams. The M_V scale assumes $(m-M)=18.4$ and $A_V \sim 0.2$. The young and old populations of the LMC are easily distinguished in the (B–V) and (V–R) colors. Evolutionary tracks of Bertelli et al. (1994) for $Z=0.001$, age=8 Gyr and $Z=0.008$, age=0.5 Gyr populations are overlaid on the (B–V) color-magnitude diagram for reference.

The *HST* observations occurred between orbital phase 0.30 and 0.36, a flat region between the primary and secondary minima, according to the light curve and ephemeris of Schmidtke et al. (1993). Our V and R magnitudes agree with out-of-eclipse magnitudes of Cowley et al. (1991) and Schmidtke et al. (1993). The (B–V) and (V–R) colors of CAL 87 place it among other ordinary LMC main sequence stars of $M_V \sim 0$, but the (U–B) color clearly sets this object apart as something unusual.

While Companions A and B have similar U magnitudes, their (B–V) and (V–R) colors differ considerably. Their respective locations in the color-magnitude diagram suggest that Companion A is an old-population red giant, while Companion B is still on the main sequence. Our colors indicate that Companion A is a mid-G type subgiant. The colors for Companion B are not easily matched to those of any normal star, but the photometric errors are sufficiently large that late-A star colors fit within 2σ error bars. There is no obvious motivation to suspect that A or B are related to the X-ray source. Reference stars 1 and 3 from Cowley et al. (1990) also appear in the PC field of view and appear high on the red giant branch in the CM diagram. For the sake of completeness, we provide in Table 1 the *HST* magnitudes for these objects as well.

The contamination by Companions A and B to the group when CAL 87 is out of eclipse is small but not negligible: CAL 87 contributes 80% and 75% of the total light of the group in V and R respectively. However, during eclipse, there is very significant contamination of the light from CAL 87 by both companions. As we have only uneclipsed observations from *HST*, we must combine our maximum light, uncontaminated photometry of all 3 stars with published reports of the eclipse depths to infer the uncontaminated CAL 87 eclipse depth as a function of color. This in turn is complicated by a variety of conflicting reports in the literature for the observed “CAL 87” eclipse depth; some but not all of the observers attempt to correct these values for contamination by Companion A (past observers have been unaware of Companion B). We use the eclipse depths $\Delta B=1.32$, $\Delta V=1.20$, and $\Delta R=0.99$ from Cowley et al. (1990), derived from measurements which

treated the group as a single source, rather than relying on attempts from ground-based data to deconvolve the components. These assumptions then permit an inferred decomposition of the 3 stars at minimum light, to complement our direct observation of the 3 objects at CAL 87 maximum light. These results are shown in Table 2. In addition to results for each star separately and their sum, we also display results for CAL 87 + B, as these objects cannot easily be separated in ground-based data. The table also provides our best inference from the decomposition for the expected uncontaminated CAL 87 eclipse depths, for use in future modeling.

The data of Table 2 confirm the suspicion of Cowley et al. (1990) and Cowley et al. (1991) that their optical and near IR spectra are heavily contaminated by sources not in the CAL 87 system. Our observed colors indicate that Companions A and B are early-G and late-A stars, respectively; at least star A almost surely exhibits many absorption lines in common with those that Cowley et al. (1990) report in their blended spectrum of all 3 objects near CAL 87. Thus the explanation by Cowley et al. (1991) that the failure of their ground-based observations of the Ca IR triplet to reveal radial velocity variations is due to contamination is probably correct, due not only to the interference of continuum from the companions, but also due to the appearance of these same spectral features in these nearby stars.

A perhaps more intriguing issue is whether the past estimates of the spectral type of the nondegenerate star in CAL 87 are also affected by the two contaminating companions. The inference that CAL 87 contains a late-F or early-G star is due to the detection of Ca H & K and the G-band by Cowley et al. (1990) in minimum light ground-based spectra, which we now understand to in fact contain 40% contamination at these wavelengths by two unrelated early-G and late-A stars, at least one of which contains these same spectral features. Furthermore, it is likely that some, perhaps even most, of the remaining 60% of the B light comes from an incompletely eclipsed accretion disk. Some of the absorptions seen in the ground-based spectra may come from the CAL 87 secondary, but a careful reconsideration of this issue may now be warranted, especially because the inference that the unseen X-ray object is a black hole depends crucially on the inferred spectral type of this star. Van den Heuvel et al. (1992) presciently predicted that the observed absorption spectrum might come from a superposed companion, and we now at least partially verify this conjecture.

3.3. NP Ser

GX17+2 (=X1813-140) is a classic LMXRB (radio emission, X-ray bursts, “Z-source” X-ray spectrum, quasi-periodic X-ray oscillations, etc.) that was optically identified more than twenty years ago (Tarengchi & Reina 1972; Davidsen et al. 1976) with a $V \sim 17.5$ G star, now known as NP Ser, on the basis of an excellent X-ray position, and subsequently a sub-arcsecond radio position (Hjellming 1978). There is one problem, however: the optical “counterpart” stubbornly refuses to show any obvious and repeatable photometric or spectroscopic abnormalities (*e.g.*, Margon 1978), despite the estimate of $L_x/L_{opt} \sim 3000$ (Bradt & McClintock 1983). Imamura et

al. (1987) reported a single, odd optical spike of duration 3 minutes in a $10''$ aperture around this object, an observation to our knowledge not replicated or confirmed in the last decade. Naylor et al. (1991) report possible IR variability, and colors inconsistent with a single, normal star. They also suggest NP Ser may be a superposition on the X-ray source, based on incompatible absorption inferred for the optical and X-ray objects. Penninx et al. (1988) are of the opinion that there is no plausible optical counterpart.

At $b = 1^\circ$ and a distance of many kpc, NP Ser is a clear candidate for an accidental superposition. Despite the high angular resolution achieved with these PC observations, NP Ser appears in our data to be a single object, with no significant deviations from the typical WFPC2 PSF of $0''.074$ FWHM. By subtracting a Tiny TIM model PSF, we set an upper limit on a possible second nearby source which might be the real optical counterpart as follows: for $r > 0''.4$, $R > 23.5$; $0''.15 > r > 0''.4$, $R > 22.5$; $0''.04 > r > 0''.15$, $\Delta R > 30 \times r$ where ΔR is the magnitude difference between NP Ser and a possible counterpart. Thus if Naylor et al. (1991) are correct regarding a chance superposition, the alignment may be extremely precise; however, see our astrometric comments below.

Accurate X-ray coordinates ($4''$ radius for 90% confidence error circle) for GX 17+2 are available from reprocessed *Einstein* HRI data in the HRICFA database obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA-Goddard Space Flight Center. Grindlay & Seaquist (1986) used the VLA to determine $0''.1$ accuracy coordinates for a 6 cm radio source within the *Einstein* error circle. The original optical position of Tarengi & Reina (1972) agrees with the radio coordinates to within $0''.5$. However, after an independent positional measurement of NP Ser using the image data and astrometric solutions used to generate the *HST* Guide Star Catalog (GSC) (Lasker et al. 1990), we find a larger-than-expected discrepancy ($2''$) between the optical and radio positions. Table 3 lists the published coordinates mentioned above as well as our GSSS position.

In an investigation of the accuracy of GSC astrometry, Russell et al. (1990) compare the difference between 48 compact radio source coordinates and their known optical counterpart positions measured on the GSC source plates. They find that the differences have $\sigma_\alpha = 0''.63$, $\sigma_\delta = 0''.58$, although they do find that two of the 48 sources have a deviation of $2''$. Furthermore, GX 17+2 is well inside the central 50% plate area region where other astrometric comparisons in Russell et al. (1990) have $\sigma_\alpha = 0''.55$, $\sigma_\delta = 0''.53$.

Using an extraction from the digitized plates used to generate the *HST* GSC (Lasker et al. 1990), we have transferred the astrometric solution in that image to a deeper R CCD image, kindly provided by M. Shara. The transfer and measurement errors on the CCD are negligible compared with systematic errors in the GSSS astrometry. Although the position in Tarengi & Reina (1972) agrees with the radio coordinates to within $0''.5$, and Grindlay & Seaquist (1986) cite a private communication photographic determination which claims agreement to within $0''.5$, we find a $\sim 2.5\sigma$ discrepancy in *each* coordinate α and δ ($\sim 3.5\sigma$ total), which, while not alarming,

is worthy of note, particularly since NP Ser refuses to show any photometric or spectroscopic peculiarities. A fundamental redetermination of the radio and optical positions seems worthwhile, and perhaps might yield a surprise.

4. CONCLUSION

Our imagery of V1727 Cyg reveals no close companions, and our photometry together with an FOS spectrum in the 2300–3300 Å range is consistent with an F8 IV type star reddened by $E(B-V) \sim 0.3\text{--}0.4$. Absorption line depths are similar to the IUE comparison spectrum, suggesting that most of the light is coming from the F8 star. For CAL 87 we provide photometry for two close companions which contribute up to 50% of the flux during eclipse. Past inferences on the spectral type of the nondegenerate star, and thus the system masses, may be influenced by this contamination. For NP Ser, no additional objects which might be related to the X-ray source are revealed, but we point out a $\sim 3.5\sigma$ positional discrepancy between the radio coordinates and the optical coordinates measured with the *HST* Guide Star Catalog source data.

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Table 1. Photometry

Object	Reference	U	B	V	R	U–B	B–V	V–R
V1727 Cyg	This work (<i>HST</i> WFPC2)	19.12	18.78	17.90	17.27	0.34	0.88	0.62
	Cowley & Schmidtke (1990)		18.85	17.91			0.95	
	Chevalier et al. (1989)		18.88	17.96	17.22		0.96	0.74
	Kaluzny (1988)	18.98	18.90	17.94	17.08	0.08	0.96	0.86
	Thorstensen et al. (1979)		18.81	17.88			0.93	
CAL 87 (maximum light)	This work (<i>HST</i> WFPC2)	17.99	18.94	18.87	18.73	−0.95	0.07	0.14
	Callanan et al. (1989) ^a		18.9	19.05			−0.15	
	Cowley et al. (1990) ^a	18.30	19.04	18.90	18.78	−0.74	0.14	0.12
Companion A	This work (<i>HST</i> WFPC2)	21.93	21.74	20.90	20.33	0.19	0.84	0.57
		(0.36)	(0.08)	(0.04)	(0.03)	(0.37)	(0.09)	(0.05)
	Cowley et al. (1990)		22.0	21.0	20.5		1.0	0.5
	Cowley et al. (1991)		21.5	20.8	20.2		0.7	0.6
Companion B	This work (<i>HST</i> WFPC2)	21.91	21.89	21.81	21.46	0.02	0.08	0.35
		(0.25)	(0.08)	(0.07)	(0.06)	(0.26)	(0.11)	(0.09)
Ref. star 1	This work (<i>HST</i> WFPC2)	19.46	18.64	17.59	16.96	0.82	1.05	0.63
	Cowley et al. (1990)	19.61	18.67	17.51	16.93	0.94	1.16	0.58
Ref. star 3	This work (<i>HST</i> WFPC2)	18.88	18.30	17.37	16.81	0.58	0.93	0.55
	Cowley et al. (1990)	18.93	18.26	17.27	16.76	0.67	0.99	0.51
NP Ser	This work (<i>HST</i> WFPC2)	19.50	18.63	17.42	16.65	0.87	1.21	0.77
	Margon (1978)	19.80	18.77	17.51		1.03	1.26	

^a Includes light from Companions A and B

Table 2. Decomposition of the Light in the CAL 87 Region

Object	U	B	V	R
Out of Eclipse Magnitudes				
CAL 87	17.99	18.94	18.87	18.73
A	21.93	21.74	20.90	20.33
B	21.91	21.89	21.81	21.46
CAL 87 + B	17.96	18.87	18.80	18.66
CAL 87 + A + B	17.93	18.80	18.65	18.44
Eclipse Minimum Magnitudes				
CAL 87	. .	20.71	20.71	20.39
A	. .	21.74	20.90	20.33
B	. .	21.89	21.81	21.46
CAL 87 + B	. .	20.39	20.37	20.05
CAL 87 + A + B	. .	20.12	19.85	19.43
Fraction of Total Light (CAL 87 + A + B) Out of Eclipse				
CAL 87	0.95	0.88	0.82	0.76
A	0.03	0.07	0.13	0.17
B	0.03	0.06	0.05	0.06
Fraction of Total Light (CAL 87 + A + B) at Eclipse Minimum				
CAL 87	. .	0.58	0.45	0.41
A	. .	0.22	0.38	0.44
B	. .	0.20	0.16	0.15
Inferred Uncontaminated Eclipse Depths (mag)				
CAL 87	. .	1.52	1.57	1.40

Table 3. Available Positions for NP Ser

Source	$\alpha(2000)$ 18 ^h 16 ^m	$\delta(2000)$ −14°02′	Stated Error	$\Delta\alpha$ from radio	$\Delta\delta$ from radio	Δ_{tot} from radio
VLA 6 cm ^a	1 ^s 334	10′′69	0′′1	–	–	–
X-ray ^b	1 ^s 2	11′′15	4′′	1′′95	0′′46	2′′00
optical ^c	1 ^s 306	10′′88	0′′6	0′′41	0′′19	0′′45
optical ^d	1 ^s 439	11′′92	0′′55	−1′′53	1′′23	1′′96

^a Grindlay & Seaquist (1986)

^b HRICFA Database at HEASARC

^c Tarenghi & Reina (1972)

^d This work using CCD and GSSS images

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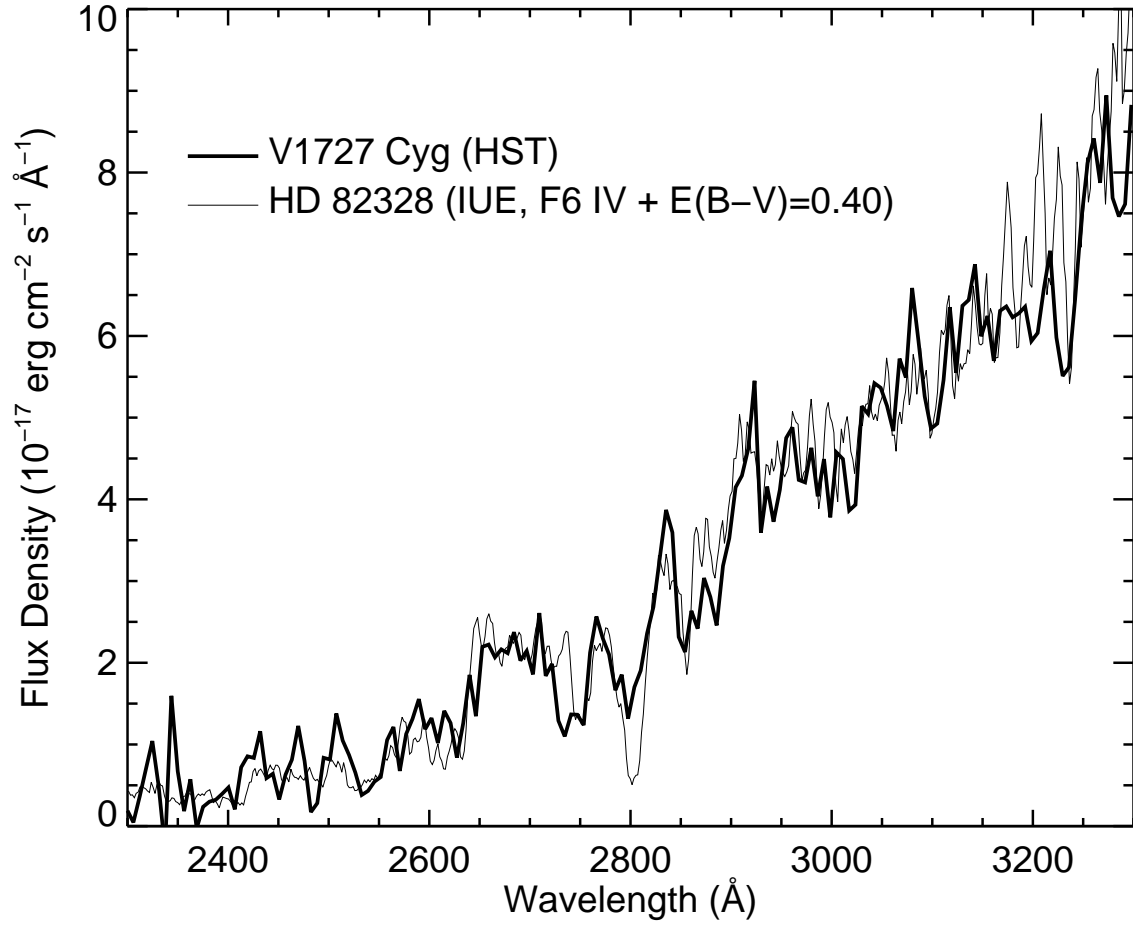


Fig. 1.— *HST* spectrum of V1727 Cyg and an IUE comparison spectrum (LWR 15500) of an F6 IV star (HD 82328) which has been reddened by $E(B-V)=0.40$ and scaled to the V magnitude of V1727 Cyg.

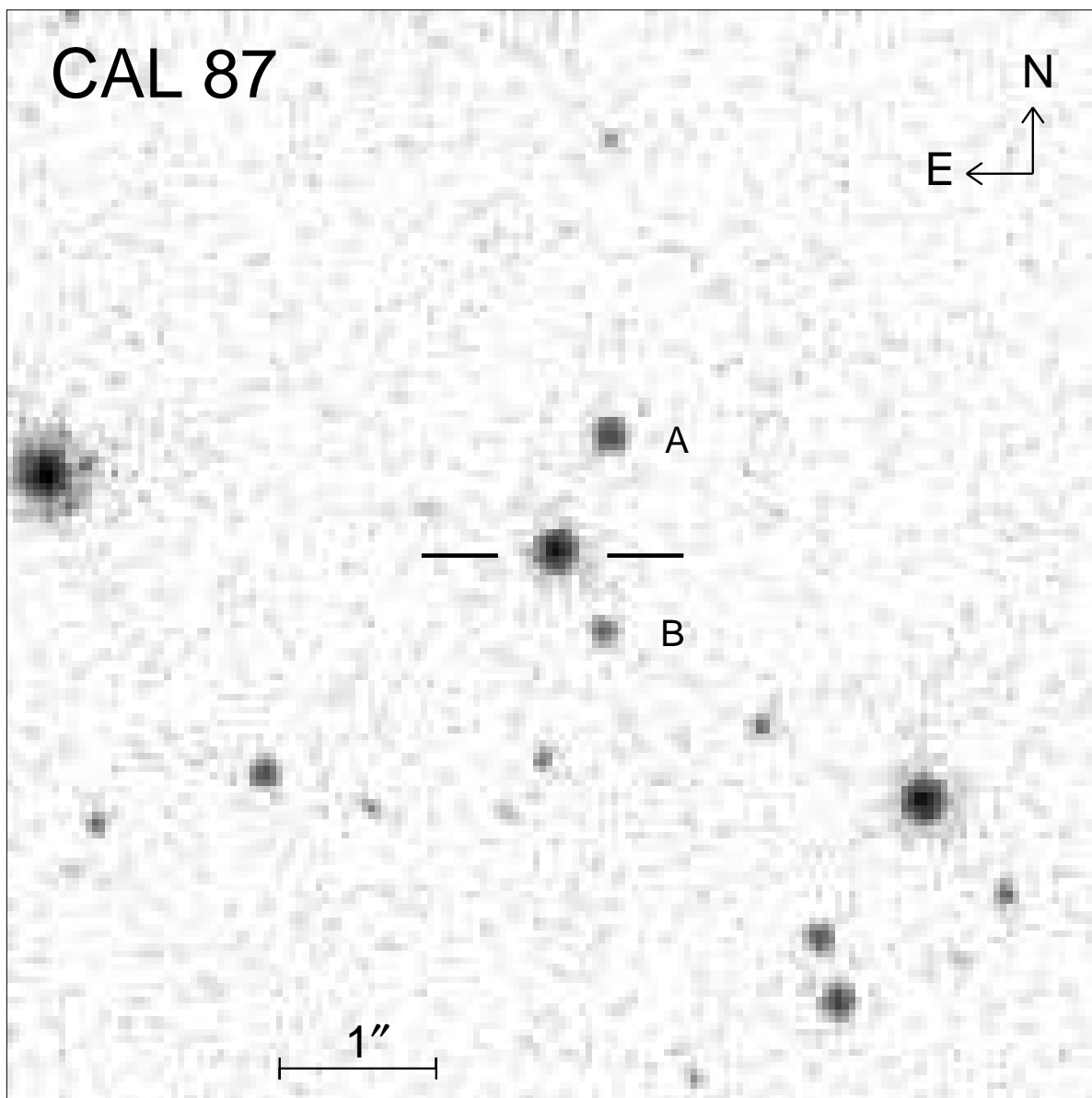


Fig. 2.— *HST* WFPC2 image of CAL 87 and the surrounding $7'' \times 7''$ region in the F675W filter. CAL 87 is in the center; close Companions A (Cowley et al. 1991) and B (this work) are separated from CAL 87 by $0''.88$ and $0''.65$ respectively. Our photometry argues against A or B having any association with the X-ray source.

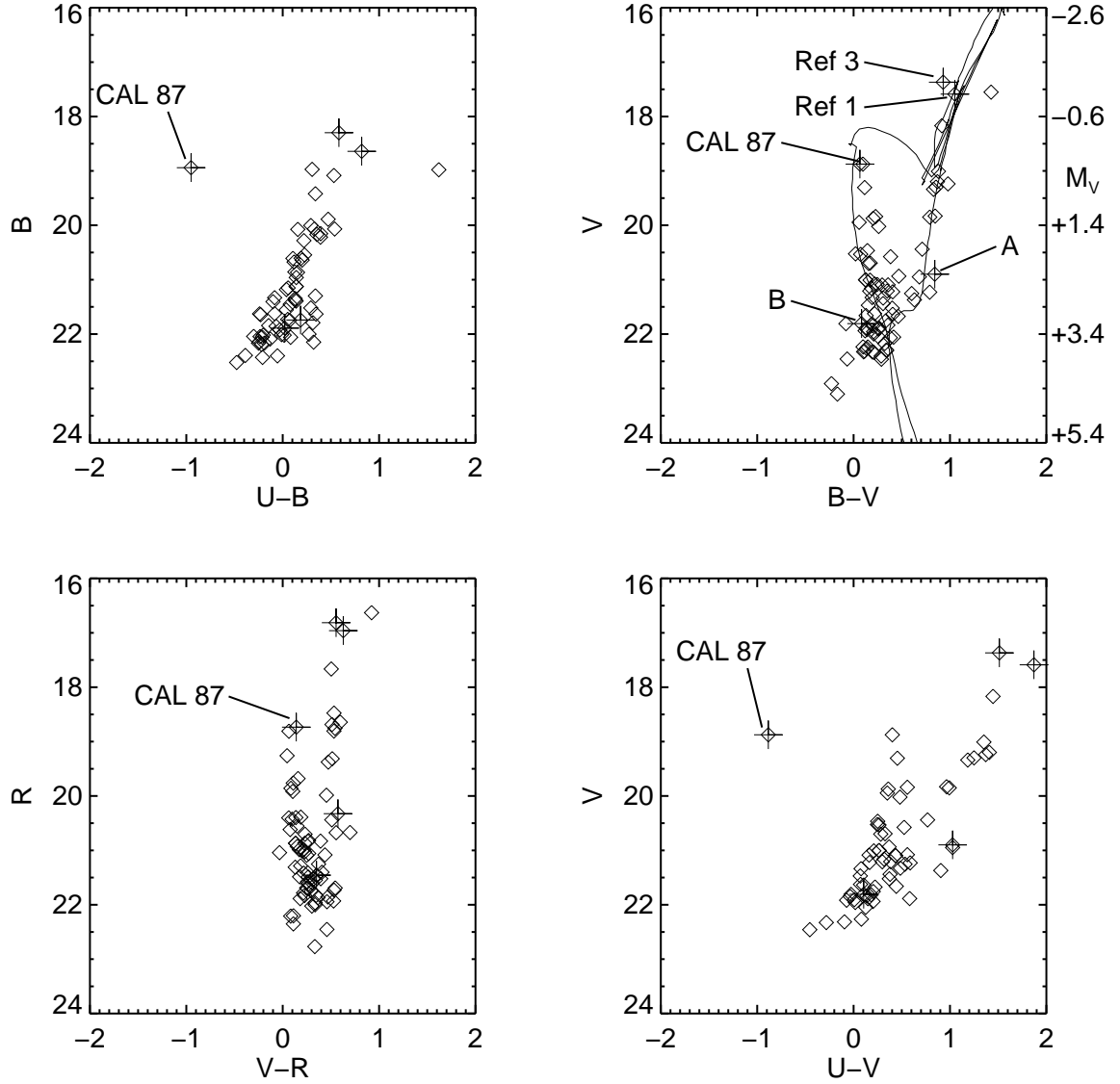


Fig. 3.— Color-magnitude diagrams in four colors for objects on the PC chip near CAL 87. Objects discussed in the text are labelled. Evolutionary tracks, detailed in the text, are drawn for reference. The M_V scale assumes $(m-M)=18.4$ and $A_V \sim 0.2$. Note the distinct position of the X-ray source in the $(U-B)$ diagram.